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GPS NAVIGATION INITIATIVES AT GODDARD SPACE FLIGHT CENTER FLIGHT DYNAMICS DIVISION*

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The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) is pursuing the application of Global Positioning System (GPS) technology to improve the accuracy and economy of spacecraft navigation. High-accuracy autonomous navigation algorithms are being flight qualified in conjunction with GSFC's GPS Attitude Determination Flyer (GADFLY) experiment on the Small Satellite Technology Initiative Lewis spacecraft, which is scheduled for launch in early 1997. Preflight performance assessments indicate that these algorithms can provide a real-time total position accuracy of better than 10 meters (1σ) and velocity accuracy of better than 0.01 meter per second (1σ), with selective availability at typical levels. This accuracy is projected to improve to the 2-meter level if corrections to be provided by the GPS Wide Area Augmentation System (WAAS) are included.

In addition, GSFC FDD has used object-oriented analysis and design technologies to define a modular software architecture that supports the development of highly reusable GPS navigation components. Work is in progress to develop a high-accuracy GPS navigation application based on this architecture, which can be provided to any spacecraft project to support real-time autonomous navigation.

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INTRODUCTION

Autonomous navigation has the potential both to increase spacecraft navigation system performance and to reduce total mission cost. By eliminating the need for routine ground-based orbit determination and special tracking services, autonomous navigation can streamline spacecraft ground systems. Autonomous navigation products can be included in the science telemetry and forwarded directly to the scientific investigators. In addition, autonomous navigation products are available onboard to support other autonomous capabilities, such as attitude control, maneuver definition and control, and communications signal acquisition.

The Global Positioning System (GPS) is becoming a more attractive autonomous navigation option for National Aeronautics and Space Administration (NASA) spacecraft due to the recent declaration that the GPS is fully operational. Currently, roadblocks to the use of GPS on NASA spacecraft include inadequate accuracy and reliability of commercial receiver products for high-precision instrument pointing and state prediction applications, lack of standardization in the products available from commercial GPS receivers, and lack of reusable GPS navigation flight software and ground support software.

The Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) has spent several years developing high-accuracy autonomous navigation systems for spacecraft using NASA's space and ground communications systems and is enhancing these systems to support spacecraft using GPS. A near-term goal is to flight qualify a GPS Standard Positioning System (SPS) receiver with NASA-developed navigation algorithms to provide real-time spacecraft position and velocity accuracies that adequately meet both the high-precision instrument pointing and state prediction requirements. Accuracy improvement is achieved through the implementation of a sophisticated real-time Kalman filter with high-fidelity state dynamics modeling.

The FDD has implemented these algorithms in prototype GPS navigation flight software, which executes within the resource constraints of currently available flight processors (e.g., <400 kilobytes memory and <0.5 million instructions per second). Preliminary assessments indicate that these algorithms can provide real-time onboard spacecraft navigation accuracies in the 10-meter (1σ) range using measurements from the GPS SPS. These navigation algorithms are being flight qualified in conjunction with GSFC's GPS Attitude Determination Flyer (GADFLY) experiment on the Small Satellite Technology Initiative Lewis (SSTI Lewis) mission, currently scheduled for launch in early 1997. In support of the GADFLY experiment, the FDD is also assessing the quality of the measurement and solutions provided by the commercial GPS receiver on the SSTI Lewis spacecraft.

The FDD is currently evaluating algorithm enhancements to improve GPS navigation accuracy and reliability. Accuracy improvements under investigation include the use of measurement corrections that will be provided by the Federal Aviation Administration's GPS Wide Area Augmentation System (WAAS). Reliability improvements under investigation relate to self-initialization of the Kalman filter processing and autonomous fault detection and recovery.

In addition, to promote rapid, cost-effective deployment of GPS technology, the GSFC FDD and Mission Operations Division have jointly investigated the feasibility of defining standard data interface formats and engineering modular software components to support both flight and ground GPS navigation applications. A software architecture has been developed, and implementation of reusable autonomous navigation system components is in progress.

This paper describes these initiatives and discusses the associated accomplishments.

GPS NAVIGATION ALGORITHMS

The basic GPS SPS commercial receiver computes the real-time three-dimensional spacecraft position and receiver time bias by solving a set of simultaneous equations constructed using pseudorange measurements to a minimum of four GPS space vehicles (SVs). These products are often referred to as the *geometric*, *point*, or *unfiltered* solutions. The major source of error in the GPS SPS measurements arises from the selective availability (SA) corruption applied to the signals and ephemerides to limit geometric solutions to approximately 100 meters (two-dimensional, 95 percent of the time) when SA is enabled. Typically, GPS receiver vendors advertise three-dimensional position accuracies on the order of 150 meters (1σ).

Because the geometric solutions are derived from measurements at a single time, they produce relatively poor velocity solutions, as compared with typical filtered orbit determination solutions. In addition, the geometric solutions can undergo significant discontinuities when the set of four GPS SVs used in the solution changes. Although the real-time position accuracy achievable using the basic geometric solution approach is adequate for some onboard applications, the position discontinuities are not acceptable for high-precision instrument pointing applications. In addition, the poor velocity accuracies are not adequate for navigation applications that require prediction of the real-time spacecraft state, such as view period prediction and maneuver planning.

The navigation algorithms discussed in this paper were developed by the GSFC FDD to meet SSTI/Lewis' real-time accuracy goal of better than 20 meters (1σ) in position and 0.03 meter/per second (1σ) in velocity using GPS SPS with SA a typical levels. These algorithms are based on mature onboard navigation systems developed for spacecraft using NASA's space and ground communications systems. The highly successful experiment on the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) spacecraft flight qualified high-accuracy algorithms for autonomous navigation using the Tracking and Data Relay Satellite System (TDRSS) and/or ground station carrier signals (Ref. 1).

These navigation algorithms consist of the following core components:

- An extended Kalman filter (EKF) augmented with physically representative models for the gravity, atmospheric drag, and time bias and drift state process noise to provide a realistic state error covariance
- A high-fidelity state dynamics model to reduce sensitivity to measurement errors and provide high-accuracy velocity estimates, permitting accurate state prediction during signal outages or degraded coverage
- Initialization and enhanced fault detection capabilities using instantaneous geometric GPS solutions

The impact of SA clock dithering on the pseudorange measurement is typically about 25 meters (1σ), with a correlation time of approximately 5 minutes. The impact on the Doppler measurement is approximately 0.15 meter per second. The EKF algorithm samples measurements from a specific SV, nominally at a 5-minute rate, to reduce the correlation between the SA-induced measurement errors. SA clock dithering is treated as white noise without the addition of filter states or colored noise models. Real-time state prediction occurs once per second. State estimation is performed at regular intervals, e.g., every 30 seconds, using measurements to the selected GPS SV. Table 1 summarizes the set of algorithms selected to meet the GPS navigation performance goals. Detailed mathematical specifications are defined in Reference 2.

Table 1
SUMMARY OF AUTONOMOUS NAVIGATION ALGORITHMS

Algorithm Type	Algorithm
Primary coordinate system	• Mean equator and equinox of J2000.0 with analytic coordinate transformations
Primary time system	• Coordinated universal time (UTC)
Numerical integrator	• Runge-Kutta 4^{th}-order
Filter spacecraft acceleration model	• Joint Gravity Model-2 (JGM-2) nonspherical geopotential up to degree 30 and order 30 • Earth, solar, and lunar point masses with analytic ephemeris • Solar radiation pressure • Analytic representation of Harris-Priester atmospheric density
Spacecraft state transition matrix	• Semianalytic formulation including J_2 and Earth point mass acceleration partial derivatives
Estimator	• Extended Kalman filter with physically realistic process noise and factored covariance matrix
Estimation state	• User position and velocity vectors • Atmospheric drag coefficient correction • GPS receiver time bias and time bias drift corrections
State process noise model	• Earth gravity model errors • Random walk model for atmospheric drag correction and time reference bias and drift • Maneuver position and velocity variances uplinked prior to maneuver
Measurement model	• GPS pseudorange and Doppler with GPS receiver time and time bias and drift corrections • Geometrical editing of measurements with high ionospheric errors
Real-time spacecraft acceleration model	• Earth point mass and J_2

Processing of raw pseudorange measurements from existing GPS receivers on the EP/EUVE and TOPEX/POSEIDON (T/P) spacecraft indicates that these navigation algorithms can provide accuracies of 10 meters (1σ) in total position and 0.01 meter (1σ) per second in total velocity with SA at typical levels (Ref. 3). FDD is currently evaluating algorithm enhancements to further improve GPS navigation accuracy and reliability. The real-time accuracy improvement to be gained by using a GPS SPS receiver augmented to receive SA measurement corrections broadcast by GPS WAAS was assessed and is discussed in the GPS WAAS Analysis section of this paper. This study indicates that accuracies of 2 meters (1σ) in total position and 0.002 meter per second (1σ) in total velocity are achievable using the baseline algorithms. Similar accuracies are achievable if the baseline algorithms are used with the restricted, uncorrupted GPS Precise Positioning Service (PPS). To achieve real-time onboard accuracies of better than 2 meters (1σ), the following improvements to the baseline algorithms are needed: (1) modeling of the instantaneous position of the GPS antenna phase centers with respect to the center of mass of the spacecraft, (2) improvements in the nonspherical geopotential model, and (3) modeling of the spacecraft thrust during maneuvers.

Reliability improvements under investigation relate to self-initialization of the Kalman filter processing and autonomous fault detection and recovery. The baseline navigation algorithms use the GPS receiver's geometric solution to initialize the Kalman filter processing and to support autonomous fault detection. Experience with actual GPS geometric solutions, described in the GADFLY/GEODE Performance Assessment section of this paper, has shown that filter initialization using the receiver's current geometric point solution is not always successful, primarily because of the sensitivity of the estimation process to the initial receiver clock bias and drift values, which are not always available. In addition, geometric solutions are not available if fewer than four GPS SVs are in view.

To eliminate any dependence on the GPS receiver's point solutions, the geometric solution capability should be integrated with the baseline navigation algorithms. In this way, these algorithms can be the source for the best state solution at any time, whether it is a geometric solution or a filtered solution. FDD is currently developing and evaluating initialization algorithms, including geometric solution algorithms, smoothing\filtering of the geometric solutions, and geometric-solution-independent approaches using Doppler measurements. To increase reliability and autonomy, the baseline fault detection and data validation process should be extended and a fault recovery process should be implemented in the event that filter divergence or a fatal software error is detected.

GPS ENHANCED ORBIT DETERMINATION EXPERIMENT

The SSTI Lewis spacecraft, currently scheduled for launch in early 1997, will host the GPS Attitude Determination Flyer (GADFLY) experiment. The GSFC Navigation, Guidance, and Control Branch is flying the GADFLY experiment to demonstrate the ability to provide precise time and to determine spacecraft orbit and attitude using a space-qualified GPS SPS receiver (Ref. 4). The GADFLY components include a space-qualified nine-channel GPS L1 frequency, coarse acquisition (C/A) code receiver interfaced with the primary spacecraft components via the Goddard Electronics Module (GEM). The GPS Attitude and Orbit Determination System (GPSAODS) receiver, developed by Space Systems/LORAL, is a redundant unit consisting of one GPS Tensor™ dual receiver, one four-channel preamplifier assembly, and four L1 receiving antennas. With SA at typical levels, the GPSAODS receiver should provide either real-time unfiltered (50 percent probability that position error $\leq$ 100 meters) or GPSAODS-filtered (mean position error $\leq$ 50 meters) state vectors and precise time (less than 1 microsecond error with respect to GPS time) via a 1-pulse-per-second discrete output to the Lewis spacecraft, when GPS data are available (Ref. 5 and 6).

As a secondary experiment, GSFC proposed that the GADFLY GPS receiver host the GPS Enhanced Orbit Determination Experiment (GEODE) to flight qualify the NASA-developed algorithms for high-accuracy real-time navigation. The FDD designed GEODE's prototype navigation flight software to be hosted on one of the receiver's digital receiver processor units (RPUs), a RAD6000 RISC microprocessor operating at 20 megahertz, and integrated with the GPSAODS flight software components. However, the accelerated development schedule for SSTI Lewis did not provide sufficient time to integrate and validate the GEODE flight software after delivery of the GPSAODS receiver. Therefore, downlinked GPS measurements will be processed using the GEODE flight software hosted on a surrogate flight computer.

The GEODE flight software was developed to be portable and modular to facilitate reuse on other missions and incorporation in other GPS receivers or spacecraft processors. The primary development platform is a Sun Sparcstation 10 using the Solaris 2.3 operating system. GEODE has also been executed on a Pentium-based microcomputer. The current version of the GEODE flight software compiles under the GNAT Ada95 compiler and requires about 380 kilobytes of memory. Reference 3 describes the GEODE flight software architecture and design.

GADFLY/GEODE PERFORMANCE ASSESSMENT

After launch of SSTI Lewis, the GSFC FDD will assess the on-orbit performance of the GADFLY/GEODE orbit solutions. An initial accuracy assessment will be performed by comparing the GPSAODS and GEODE solutions with moderately accurate definitive solutions obtained using S-band ground network tracking data. These S-band tracking solutions are expected to provide total position accuracies in the 25- to 50-meter (1σ) range. Subsequently, an in-depth accuracy assessment will be performed by comparing the GPSAODS and GEODE solutions with high-accuracy (i.e., submeter) solutions obtained by differential postprocessing of the GPSAODS GPS measurements together with GPS measurements obtained through the International GPS Service for Geodynamics (IGS). In addition, the noise and bias characteristics of the GPSAODS pseudorange and Doppler measurements will be analyzed.

Reference 3 discusses a preflight assessment of GEODE flight software performance by processing GPS pseudorange measurements obtained from experimental receivers flown on the EP/EUVE and T/P spacecraft. On the basis of these analyses, the expected performance of the GEODE flight software for SSTI Lewis has been projected to be 10 meters (1σ) in total position and 0.01 meter (1σ) per second in total velocity with SA at typical levels. More recently, experiments were performed in a realistically simulated flight environment to investigate both GPSAODS and GEODE flight software performance. The results from these investigations are provided in the remainder of this section.

To support checkout of the GPSAODS receiver prior to its integration with the Lewis spacecraft, a Northern Telecom GPS simulator was used to generate GPS-like radio frequency signals that the GPSAODS receiver acquired and from which it extracted and processed ambiguous pseudorange and Doppler measurements. This simulation was performed in a flight mode in which the simulator was driven by a high-fidelity ephemeris for the SSTI Lewis spacecraft. Six-hour simulations were performed without (Case 1) and with (Case 2) SA active. The GPSAODS receiver was powered on shortly before the simulations began, and the GEODE filter was initialized after the receivers' oscillators had stabilized at about one hour into the simulations.

GPSAODS Products

The accuracy of the GPSAODS geometric solutions was evaluated by comparison with the truth ephemeris on which the simulation was based. Without SA active, the geometric solution errors were 100 meters maximum and 18 meters rms in total position and 0.1 meter per second maximum and 0.04 meter per second in total velocity. With SA active, the geometric solutions errors were 380 meters maximum and 105 meters rms in total position and 9 meters per second maximum and 0.9 meter per second rms in total velocity (a five-minute excursion to 32 meters per second was observed but has not been explained and was not included in these statistics). Figures 1 and 2 provide the total position differences for the geometric solutions for Cases 1 and 2, respectively.

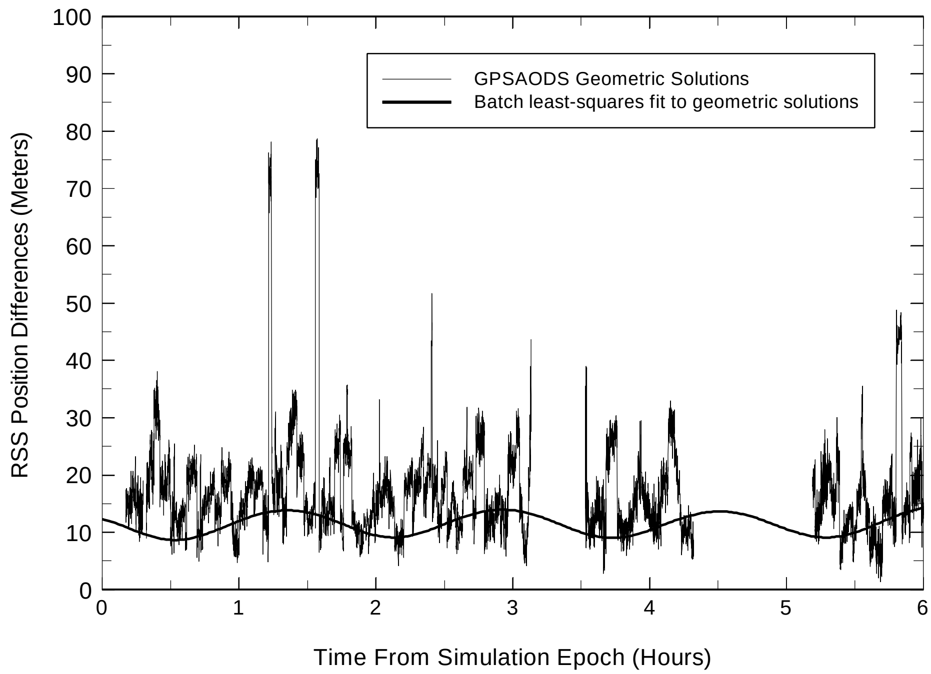

Figure 1. GPSAODS Raw Geometric Solution Versus Truth Position Differences Without SA Active

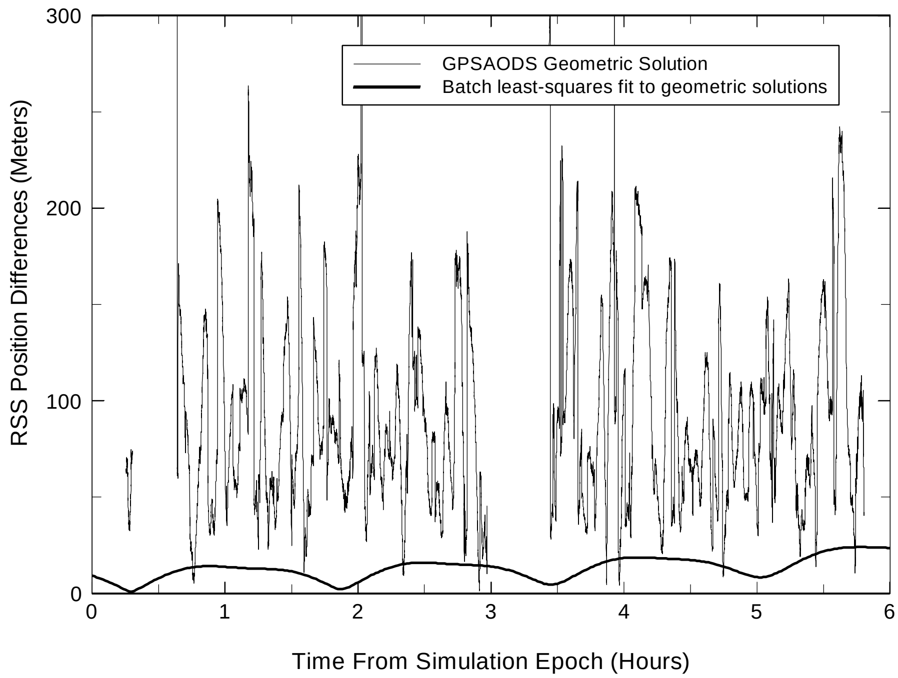

Figure 2. GPSAODS Raw Geometric Versus Truth Position Differences With SA Active

In addition, the GPSAODS geometric solutions were postprocessed as measurements in a least-squares estimator using a high-fidelity dynamic model. Without SA active, the resultant *smoothed* solution errors were 14 meters maximum and 11 meters rms in total position and 0.014 meter per second maximum and 0.013 meter per second rms in total velocity. Similarly, with SA active, maximum and rms errors were 24 and 14 meters in position and 0.026 and 0.015 meters per second in velocity. The high accuracy provided by these *smoothed* solutions suggests that comparable results could also be obtained by processing the raw geometric solutions as measurements in an onboard EKF with a high-fidelity dynamic model.

In both the smoothed and unsmoothed cases, several meters of the total rms position error are due to truncation of the output timetag to the whole millisecond. The noise characteristics of the GPSAODS raw pseudorange and Doppler measurements were also analyzed. Without SA active, the pseudorange noise was approximately 2.2 meters (1σ) and the Doppler noise was approximately 0.05 hertz (1σ).

GEODE Products

The GPSAODS ambiguous pseudorange and Doppler measurements were processed in the GEODE flight software. Without SA active, the GEODE flight software produced converged solutions with errors of 15 meters maximum and 4 meters rms in total position and 0.035 meter per second maximum and 0.009 meter per second rms in total velocity, in spite of data gaps of 0.5 and 1 hour in the 5-hour data processing time span. With SA active, the GEODE flight software produced converged solutions with errors of about 35 meters maximum and 9 meters rms in total position and 0.06 meter per second maximum and 0.03 meter per second rms in total velocity. Figures 3 and 4 show the total position errors for the GEODE solutions for Cases 1 and 2, respectively. Comparable results were obtained processing only pseudorange measurements and processing pseudorange and Doppler measurements. The receiver time bias and time bias drift rate estimates agreed well with those derived directly from analysis of the measurement data.

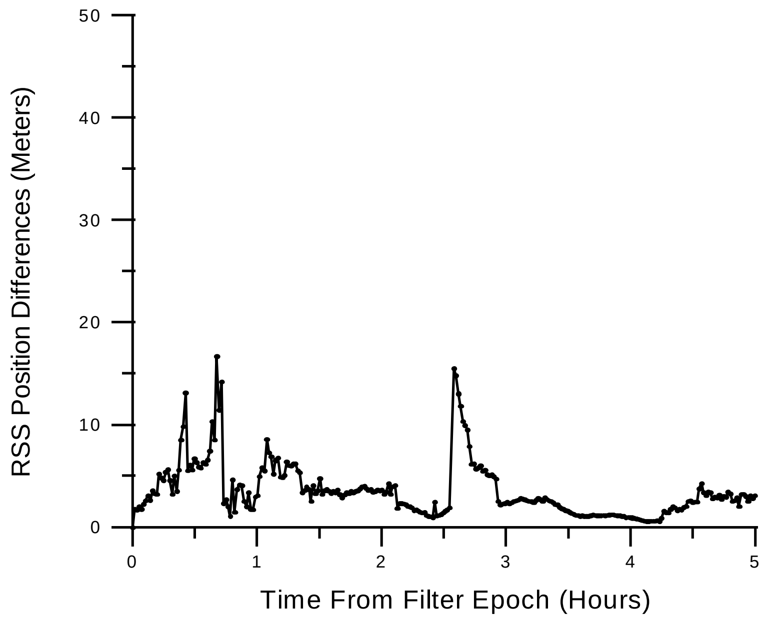

Figure 3. GEODE Solution Versus Truth Position Differences Without SA Active

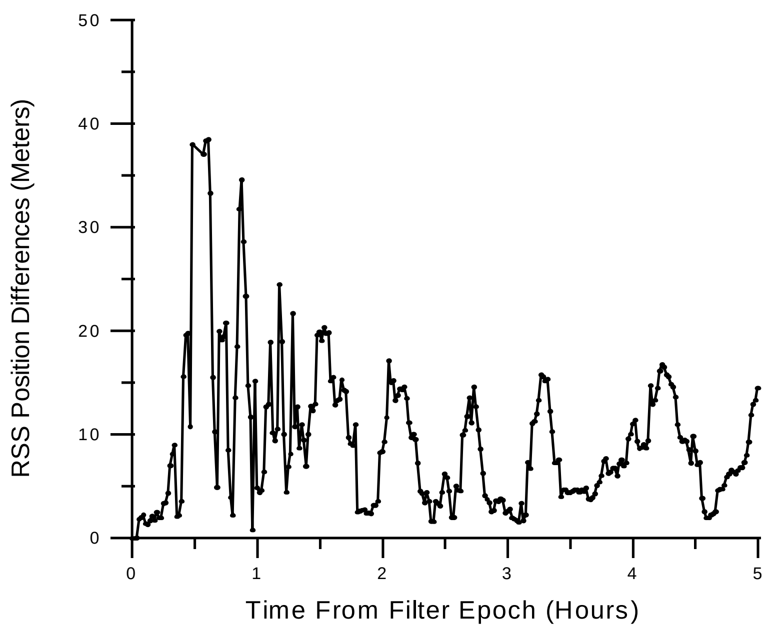

Figure 4. GEODE Solution Versus Truth Position Differences With SA Active

Figures 5 and 6 compare the total position and velocity error results for both test cases, respectively. Comparison of the raw geometric results with the GEODE filtered results clearly indicates that the GEODE's high-fidelity dynamic model significantly reduces sensitivity to SA induced measurement errors and provides high-accuracy velocity estimates.

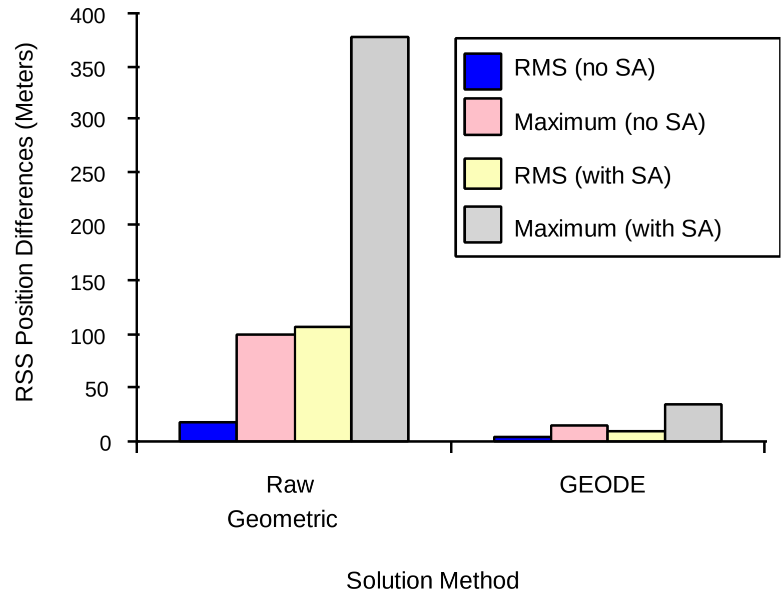

Figure 5. GPSAODS/GEODE Solution Total Position Accuracy

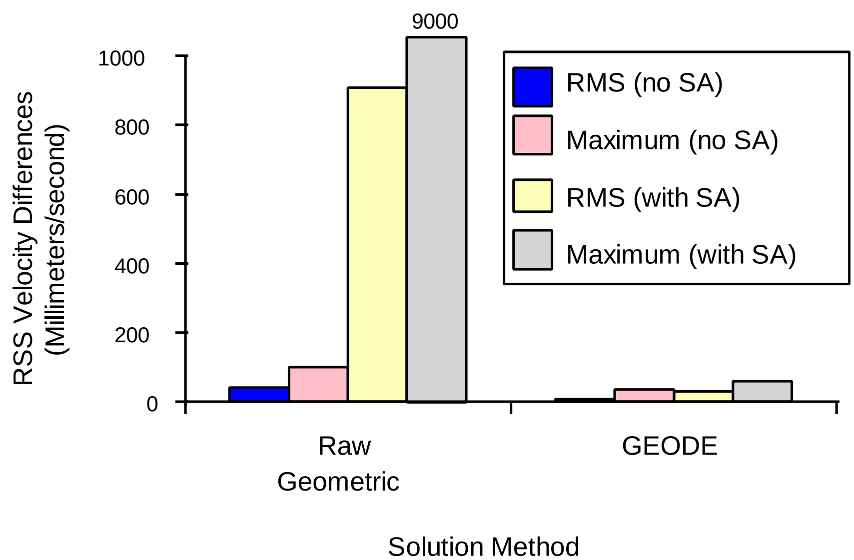

Figure 6. GPSAODS/GEODE Solution Total Velocity Accuracy

In this evaluation, the initial GEODE flight software performance was found to be very sensitive to the accuracy of the initial receiver time bias and time bias drift and the associated initial covariances. This difficulty was due to the fact that the time bias and time bias drift values are not included in the standard GPSAODS state data packet. Therefore, accurate values for the GPSAODS time bias, which ranges from ±0.5 milliseconds, and the time bias rate (approximately 0.75×10^{-6} seconds per second) were not readily available for filter initialization. However, following successful initialization, the navigation algorithm was found to be highly reliable, accurately propagating through data gaps of up to 1 hour and recovering without external intervention.

GPS WAAS ACCURACY ANALYSIS

The GPS Wide-Area Augmentation System (WAAS) is being designed and developed by the United States Federal Aviation Administration (FAA) to augment GPS SPS so that it can be used as the primary navigation sensor in conjunction with a GPS single-frequency receiver modified to receive the WAAS signals. GPS WAAS will provide the following three additional services: a GPS-like ranging function to a number of geostationary communications satellites to improve availability and reliability, differential GPS corrections to improve accuracy by reducing GPS ephemeris and clock errors (both SA induced and propagation), and integrity monitoring to improve safety (Ref. 7 and 8). The FAA WAAS program is expected to result in the initial operational capability in 1998.

The GPS measurement corrections provided by WAAS (initially by the United States WAAS, but eventually by a worldwide WAAS) can eliminate most of errors caused by SA. With SA errors removed or substantially reduced by using WAAS provided corrections, both geometric and filtered orbit solution accuracies are expected to improve significantly. The navigation performance improvement resulting from the use of WAAS corrections was investigated for the case of the proposed Earth Observer-1 (EO-1) mission. The objective of this analysis was to provide a conservative estimate of the real-time onboard navigation accuracy that is readily achievable assuming navigation algorithms/modeling errors realistic for the 1998 timeframe.

GPS pseudorange and Doppler measurements were simulated over a 2-day time span for the nominal EO-1 orbit (700-kilometer-altitude, 98-degree-inclination, near-circular). Table 2 summarizes the simulation error models used. Simulated measurement errors were consistent with the FAA's projected WAAS-correction accuracies (i.e., ≅2 meters in user effective range error (UERE)). In addition, GPS-like pseudorange and Doppler measurements were simulated for two WAAS geostationary (GEO) spacecraft using measurement errors of 1 meter rms. Two cases were investigated: US WAAS, for which WAAS corrections are limited to GPS SVs visible from the US, and Global WAAS, for which WAAS corrections are available globally. In the US WAAS case, the SA corruption was simulated at the 25-meter rms level for GPS SVs that were not visible from the US.

Table 2
GPS WAAS SIMULATION ERROR MODELS

Error Model	US WAAS	Global WAAS
WAAS-corrected pseudorange (meters rms)	2 (GPS SVs visible from US)	2 (all GPS SVs)
WAAS-corrected Doppler (hertz rms)	0.1 (GPS SVs visible from US)	0.1 (all GPS SVs)
Uncorrected pseudorange (meters rms)	25 (GPS SVs not visible from US)	Not applicable

Uncorrected Doppler (hertz rms)	1.3 (GPS SVs not visible from US)	Not applicable
WAAS GEO pseudorange (meters rms)	1	1
WAAS GEO Doppler (meters rms)	0.05	0.05
Truth Ephemeris	• 50×50 geopotential • Precise solar, lunar, and coordinate transformation data • Dynamic atmospheric density model	• 50×50 geopotential • Precise solar, lunar, and coordinate transformation data • Dynamic atmospheric density model

The GPS navigation algorithms, listed in Table 1, were used to process measurement pairs selected such that measurements from a specific GPS SV were processed no more frequently than every 300 seconds when visible. No change was made to the GEODE satellite selection algorithm; therefore, the use of corrected versus uncorrected observations is not expected to be optimal for the US WAAS case. For the US WAAS case, this produced a measurement set consisting of 33 percent WAAS corrected, 7 percent GEO, and 60 percent uncorrected measurements.

The resulting filtered solutions were compared with the truth ephemeris used in the data simulation. The total position and velocity differences between the GEODE and truth solutions were 2.2 meters and 2.1 millimeters per sec (rms) for the US WAAS case and 1.8 meters and 1.9 millimeters per sec (rms) for the Global WAAS case. These accuracy levels were found to be insensitive to the use of measurement processing rates of 1 measurement pair every 10, 30, or 70 seconds. Figures 7 and 8 show the RSS position and differences for the US WAAS and Global WAAS simulations, respectively.

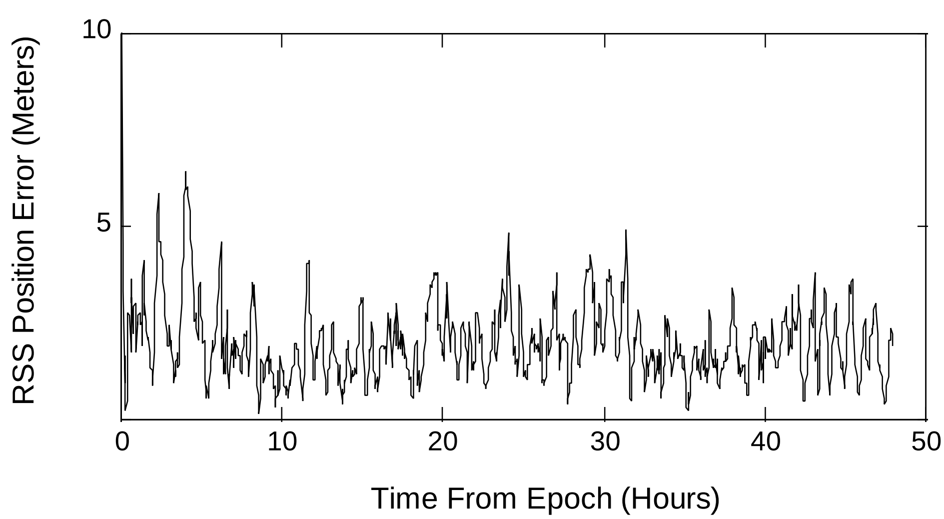

Figure 7. Position Accuracy for US WAAS Using GEODE Navigation Algorithms

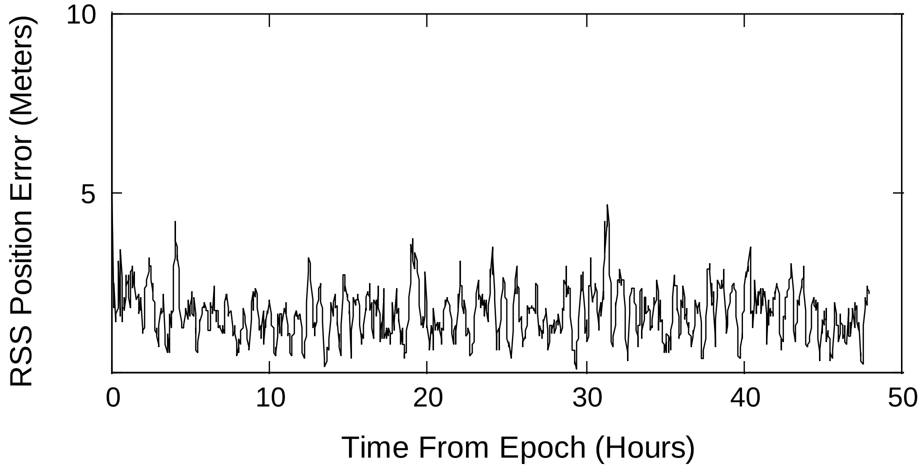

Figure 8. Position Accuracy for Global WAAS Using GEODE Navigation Algorithms

MODULAR GPS NAVIGATION SOFTWARE

To promote rapid, cost-effective deployment of GPS technology, GSFC FDD and Mission Operations Division have investigated the feasibility of defining standard data interface formats and engineering modular software components to support both flight and ground GPS navigation applications. The scope and objectives of the GPS Modular (GMOD) software initiative are as follows:

- Support the following spacecraft navigation functions: geometric position computation, state (i.e., spacecraft position and velocity and GPS receiver time bias) estimation, state prediction, orbit adjustment, and navigation performance monitoring and calibration
- Provide several levels of autonomy ranging from ground processing of downlinked GPS receiver measurements to autonomous onboard state estimation and orbit adjustment.
- Support real-time and near-real-time autonomous navigation operations to provide spacecraft navigation accuracies in the 10-meter (1σ) range using a single-frequency commercial GPS SPS receiver, with SA at typical levels. Accuracy improvements will be possible using measurements from GPS PPS- and WAAS-compatible receivers.
- Standardize external interfaces to the GPS modular software, such as the GPS measurement interface, command interface, and telemetry interface
- Facilitate reuse by building the navigation applications from a library of object-oriented modular components

The following major objectives have been accomplished, with the detailed results presented in Reference 9:

- A complete end-to-end candidate system was defined to provide spacecraft navigation using a GPS/GPS-like receiver.

- Operational configurations were developed that logically partition GPS navigation functions between flight and ground segments to support several levels of spacecraft autonomy.
- GPS data interface formats for flight or ground processing software were defined. These formats can be used to support standardization of the data interfaces from diverse GPS receivers.
- Objected-oriented analysis and design techniques were used to develop an open system architecture design that provides the flexibility to host standard navigation software components onboard or on the ground to provide a range of mission-selectable flight/ground functional partitions.

Reference 10 discusses the detailed design of the major elements of the GMOD software architecture, shown in Figure 9. This architecture has two basic forms of classes, application classes (unshaded boxes) and interface classes (dark shaded boxes). The application classes are generalized software representations (abstractions) of objects in the GMOD problem domain of spacecraft navigation. Examples of objects in this domain are (1) physical objects, such as the spacecraft, Sun, Earth, and Moon, and (2) algorithmic or abstract objects, such as integrators and estimators. Application classes can be grouped into an object-oriented hierarchy of superclasses and subclasses. For example, the Earth application class can be defined as a specific subclass of the more general superclass Solar System Body.

The interface classes encapsulate the external data interfaces and associated access methods. For example, the interface class for the GPS receiver contains the member functions that perform the data conversion needed to process receiver-specific data formats. These “interface” classes shield the application classes that compose the vast majority of the GMOD software from changes in the external interfaces in the ground and space environments; this facilitates reuse of the application classes in both environments.

The driver element is the “glue” that binds the classes and data objects into an executable application program. The driver element consists of an overall executive routine that manages the execution flow in the configured application and a set of routines that manage the data exchange between the GMOD application and the user interface/executive (ground-based applications) or the GMOD application and the flight software executive (space-based applications). As in the case with the interface classes, the driver module serves to insulate the application classes from the mission-specific computer environment.

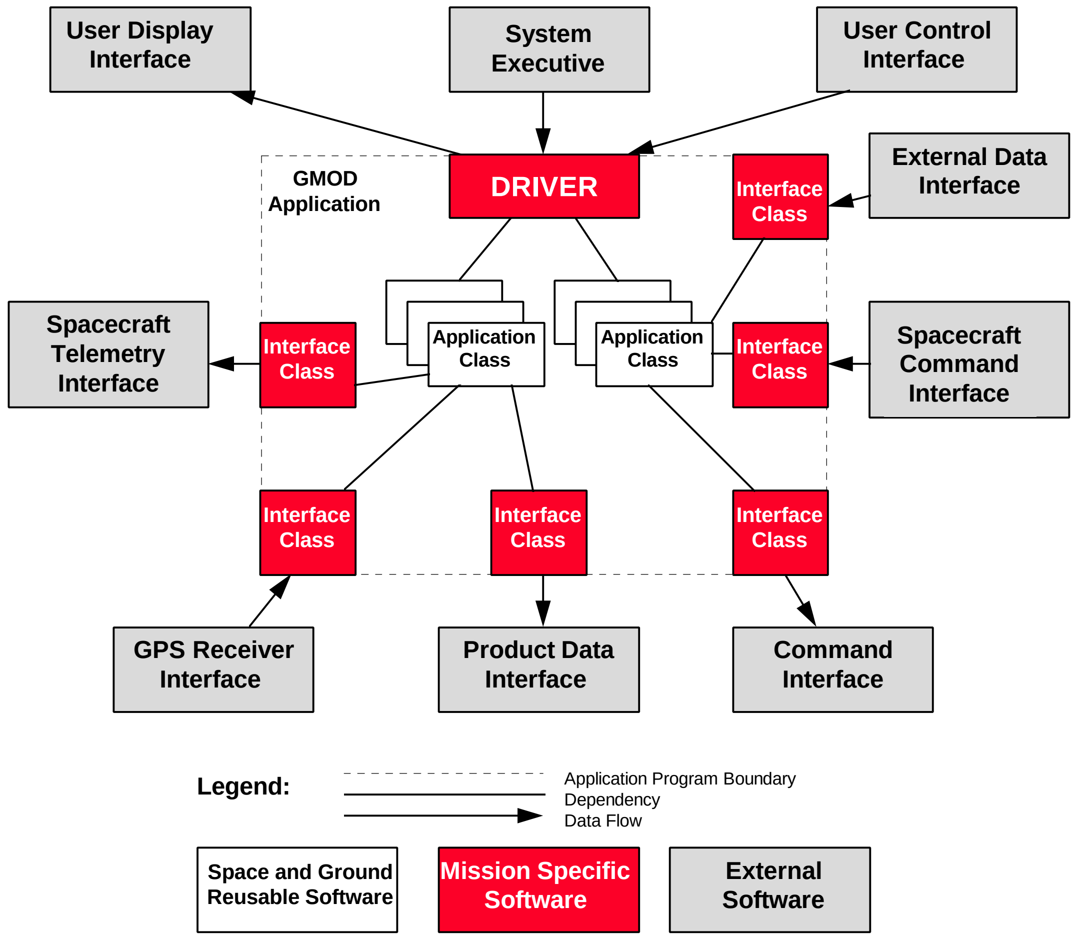

Figure 9. GMOD Software Architecture

The FDD is currently developing an autonomous navigation (GPSNAV) application using the GMOD software architecture. The C++ programming language was selected as the implementation language for the GMOD software because it fully supports object-oriented technology. The GMOD architecture is based on object-oriented concepts used successfully by the FDD to build satellite ground data system applications, for which memory and CPU resource constraints were not severe. An outstanding GMOD feasibility issue is whether full use of the C++ object-oriented implementation features will produce software applications that can execute with the resource constraints of typical flight processors. Therefore, the performance of this application will be carefully evaluated with respect to memory and CPU usage. The GPSNAV application will be made available to any spacecraft project to support real-time autonomous navigation using GPS.

FUTURE DIRECTIONS

Future directions for GSFC FDD's GPS autonomous navigation initiatives are (1) to investigate algorithm enhancements to improve onboard accuracy and reliability using GPS, (2) to participate in a cooperative effort to build a NASA miniaturized GPS receiver, and (3) to extend the autonomous navigation applications to other flight applications such as high-eccentricity orbits and relative navigation using GPS.

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REFERENCES

1. C. J. Gramling et al., "TDRSS Onboard Navigation System (TONS) Flight Qualification Experiment," *Proceedings of the Flight Mechanics/Estimation Theory Symposium 1994*, NASA Conference Publication 3265, May 17–19, 1994, p. 253–267

2. Goddard Space Flight Center, Flight Dynamics Division, 553-FDD-95/013R0UD0, *Global Positioning System (GPS) Enhanced Orbit Determination Experiment (GEODE) Mathematical Specifications*, T. Lee and A. C. Long, prepared by Computer Sciences Corporation, August 1996

3. Roger C. Hart et al., "Global Positioning System (GPS) Enhanced Orbit Determination Experiment (GEODE) on the Small Satellite Technology Initiative (SSTI) Lewis Spacecraft," *Proceedings of the ION GPS-96*, Kansas City, Missouri, September 17–20, 1996

4. Frank H. Bauer et al., "The GPS Attitude Determination Flyer (GADFLY): A Space-Qualified GPS Attitude Receiver on the SSTI Lewis Spacecraft," *ION GPS-95 Proceedings*, ION GPS-95 Conference, Palm Springs, California, September 1995

5. Space Systems/LORAL, Specification No. E101050, *GPS Attitude and Orbit Determination System and GPS Orbit Determination System (GPSAODS and GPSODS) Performance Specification*, June 5, 1996

6. Kurt Brock et al., "GPS Attitude and Orbit Determination for Space," *ION GPS-94 Proceedings*, ION GPS-94 Conference, Salt Lake City, Utah, September 20–23, 1994

7. R. Loh, V. Wullschleger, B. Elrod, M. Lage, and F. Haas, "The U.S. Wide Area Augmentation System (WAAS)", *Navigation*, Vol. 42, No. 3 (Fall 1995), pp. 435-465

8. Per K. Enge and A. J. Van Dierendonck, "Wide Area Augmentation System," *Global Positioning System: Theory and Applications*, Vol. 2, edited by B. Parkinson and J. Spilker, American Institute of Aeronautics and Astronautics, Inc.: Washington, DC, 1996

9. Son H. Truong et al., "Modular Software for Spacecraft Navigation using the Global Positioning System (GPS)," *ION GPS-96 Proceedings*, ION GPS-96 Conference, Kansas City, Missouri, September 17–20, 1996

10. Wendy C. Shoan et al., "Modular Software Architecture for Space- and Ground-Based Spacecraft Navigation Using GPS," *Proceedings of the AIAA/AAS Astrodynamics Specialist Conference*, San Diego, California, July 29–31, 1996, pp. 712–721